A new approach for weak time-lapse anomaly detection using seismic attributes: Geology and production data integrated monitoring of miscible EOR-CO_2 flood in carbonates

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Summary

Since the emergence of time-lapse, TL, seismic technology as a viable element of reservoir management, monitoring production and enhanced oil recovery programs, in carbonates, has been very challenging. Coupled effects of complicated petrophysical and/or lithofacies heterogeneities "difficult to model or image," low compressibility "high stiffness," and thinness of carbonates have made seismic monitoring a high-risk component of EOR programs requiring both highly repeatable 4D-seismic acquisition and weak anomaly-sensitive processing and interpretation approaches. Most important is the need to maximize interdisciplinary synergy among all reservoir management team members. In this study, we present a new non-differencing approach called "Parallel Progressive Blanking" (PPB) for detecting time-lapse seismic attributes anomalies. This approach is more efficient than differencing TL attributes and/or data in cases where weak anomalies are concealed by non-repeatable noise. Four 4D-seismic datasets, interpreted seismic lineaments, seismic facies, sedimentological models and production data provided a means of testing and validating the PPB approach of interpreting weak TL-seismic attributes of anomalous zones observed during a miscible EOR-CO_2 flood. Using four TL-seismic datasets and applying the PPB approach, we have successfully monitored changes in seismic response related to the miscible EOR-CO_2 bank in the Hall-Gurney Field in Kansas. A predicted "via reservoir simulation" CO_2 breakthrough in April, 2004 in well 12 and an unpredicted delayed response from well 13 have been in compliance with the interpreted spatial outline of the injected CO_2 bank. Changes in pump strategies between two seismic surveys resulted in retreating of the CO_2 plume. Relatively fine (two months) survey-to-survey time spacing has assisted qualitative estimation of both reservoir heterogeneity and robustness of implementing the PPB approach, furthermore, dynamic flood management was aided by TL-findings.

Introduction

Time-lapse (4D) seismic monitoring provides valuable information to reservoir management programs which, when delivered in a timely cost-effective manner, can play a critical role supporting dynamic reservoir management in EOR assessment and monitoring, provide more constraints on reservoir simulation, help unravel geologic details of compartmentalization, and guide placement of infill wells. Thus, cost effectiveness, a short turnaround time, and sensitivity to subtle production and/or EOR reservoir changes are critical assets of robust and economic TL-seismic application. Success of TL-seismic monitoring has been proven mainly for offshore studies of thick clastic reservoirs (Waal and Calvert, 2003; Boyd-Gorst et al., 2001) where the risk is lower (Lumley et al., 1997). TL seismic change "anomalies" observed during enhanced oil recovery or carbon dioxide sequestration in low compressibility "stiff" carbonate reservoirs are likely to be so weak that they will blend into the non-repeatable background noise on seismic attribute difference maps. Those expectedly weak TL anomalies "high risk cases" lie in what is classified as a "stretch portfolio" of time-lapse application to reservoir management practices (Waal and Calvert, 2003; Wang, 1997; Skirius et al., 1999). A key interest in today's industry is to make TL technology cheaper and more sensitive to small production effects (Calvert, 2005).

In this paper we report on the development and application of the PPB approach for monitoring EOR-CO_2 using textural interpretation of non-inversion direct TL-seismic attributes. This approach is sensitive to weak production TL-anomalies such as those expected in the case of carbonates, cost effective, and robust with respect to both residual cross-equalization differences and non-repeatable noise. Three TL-datasets and a baseline dataset integrated with production data and conceptual geologic models allowed testing of several interpretation approaches and validation of the solid support for the implementation of the PPB method for unraveling weak TL-anomalies. TL-seismic application in the miscible EOR-CO_2 program of the Hall-Gurney Field—where the target is a thin (about 5 m) shallow (about 900 m) oomoldic carbonate of the Plattsburg Formation of the Lansing-Kansas City (L-KC) Group (Dubois et al., 2001)—enabled dynamic management of the EOR flood.

Theory and Method

The established practice for implementing TL-seismic technology to EOR has supported the concept that viable application of TL requires that TL-seismic change related to production must be large enough to be detected as a magnitude difference over a considerable spatial extent. In the case of weak production TL-seismic signatures, as is often the case for carbonates, the TL anomaly is not likely to maintain a magnitude difference over a considerable spatial extent. It is not uncommon for this lower amplitude anomaly to be lower in magnitude than non-repeatable noise and residual cross-equalization differences. An approach that operates using direct (non-inversion) seismic attributes, responds to textural rather than magnitude differences, and tolerates imperfections in cross-equalization is more appropriate for weak TL-anomaly cases.

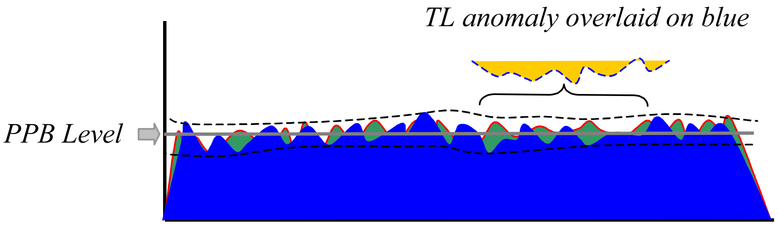

Figure 1: Schematic illustration of the underlying concept for applying the PPB method of TL-seismic anomaly detection.

The PPB approach can be illustrated (Figure 1) by placing a very weak TL anomaly over a TL attribute profile from a seismically innocuous area (blue-green). Because the amplitude of change is low (below noise fluctuations), textural differentiation is more feasible than differencing the baseline survey (green) with a TL data set (blue). The PPB method highlights weak reservoir signatures (texture), allows some suppression of background noise, and focuses the highest resolution components of the color scale on the critical range of attributes (Figure 2e).

Hall-Gurney EOR-CO_2 Flood— Applying and Validating the PPB Method

We selected the amplitude envelope or reflection strength seismic attribute because of its insensitivity to small, uncompensated phase differences between baseline and TL data sets. Advancement (Figures 2a-d) of the CO_2 plume was monitored using the PPB technique and checked for accuracy against independent production data. Integrating TL seismic interpretations with production data helps equilibrate results with real reservoir characteristics and allows development of more meaningful geologic and engineering models. For example, incorporating pressure maps, fluid composition, and flow rates of fluids between wells provides essential "ground truth" for refining the analysis and increasing confidence in the method.

Maps of the plume resulting from CO_2 injection in Hall-Gurney developed using 4-D seismic data has been consistent with:

- solvent "CO_2" breakthrough in well 12 (Figure 2c),
- interwell testing that indicated a pressure communication/ permeability barrier between wells 13 and CO_2I#1,
- reservoir simulation-based prediction that solvent "CO_2" will move northward from the CO_2 injection well,
- lower cumulative oil production observed in well 13 than previously projected for the reservoir simulation period (eight months) studied here, and
- material balance calculations integrating reservoir architecture inferred from core measurements and reservoir injection data and production data.

Similarity maps (Figure 3) possess geometries that are sinuous-to-linear, isolated pod-shaped, and apparent parabolic forms as distinguished with differing reservoir (permeability) quality, appearing consistent with small-scale depositional features that occur within ooid shoal complexes. Lithofacies changes interpreted to be associated with these similarity patterns could be a major factor controlling observed heterogeneities within the target zone. Curvature attribute seismic maps indicate lineaments (Figure 4) affecting the target zone also appear to play an important role in reservoir character and impact EOR efforts. The likely interplay of lithofacies patterns and structural elements (lineaments) in controlling reservoir character and production patterns associated with the CO_2 EOR effort is likely demonstrated by the seismically mapped movement of the CO_2 bank. Movement of CO_2 through this reservoir appears to be influenced by the elongated NE-SW trending higher similarity "seismic facies" areas (better properties) as well as the interconnecting NNE-SSW lineaments.

Conclusions

The PPB approach, though it is difficult to automate, was very effective at mapping a weak TL anomaly that otherwise would have been difficult, if at all possible, to map using more standard TL differencing. It is qualitatively efficient to apply PPB in situations where weak TL imprints are unlikely to be pronounced relative to background on difference maps. To reveal subtle TL anomaly textures, selecting a small, optimum range of high-resolution colors is essential to the successful application of PPB. It is also critical to avoid applying severe equalization methods.

One can realize that the PPB approach does preserve/enhance TL-textural imprints by avoiding non-repeatable noise differencing and color resolution focusing/sliding (Figure 2a) designed to cover the critical range of variability on an attribute map. Consistent with other TL methods, control is maintained using the PPB-modified baseline attribute horizon. Additional quality control is provided by the baseline attribute map to which PPB has also been applied in a manner that preserves maximum similarity in areas where no reservoir change is expected.

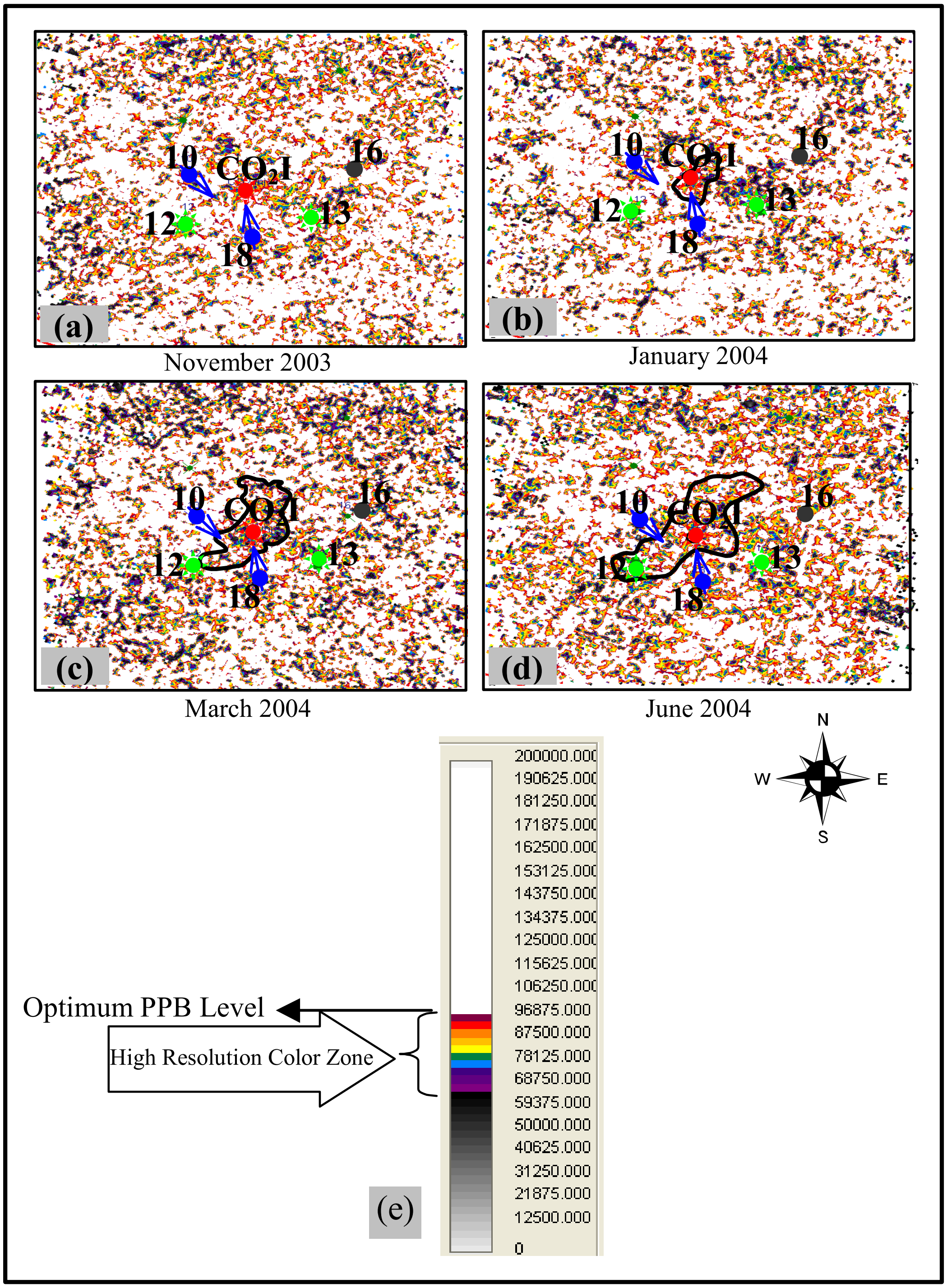

Figure 2: Applying the PPB method of TL-seismic anomalies (outlined) detection as: baseline (a); monitor surveys (b-d); amplitude envelope attribute maps after applying the PPB scale (e); CO2I well is the CO_2 injector, wells 10 and 18 water injection, wells 12 and 13 oil producers, and well 16 observation.

A new approach for time-lapse anomaly detection

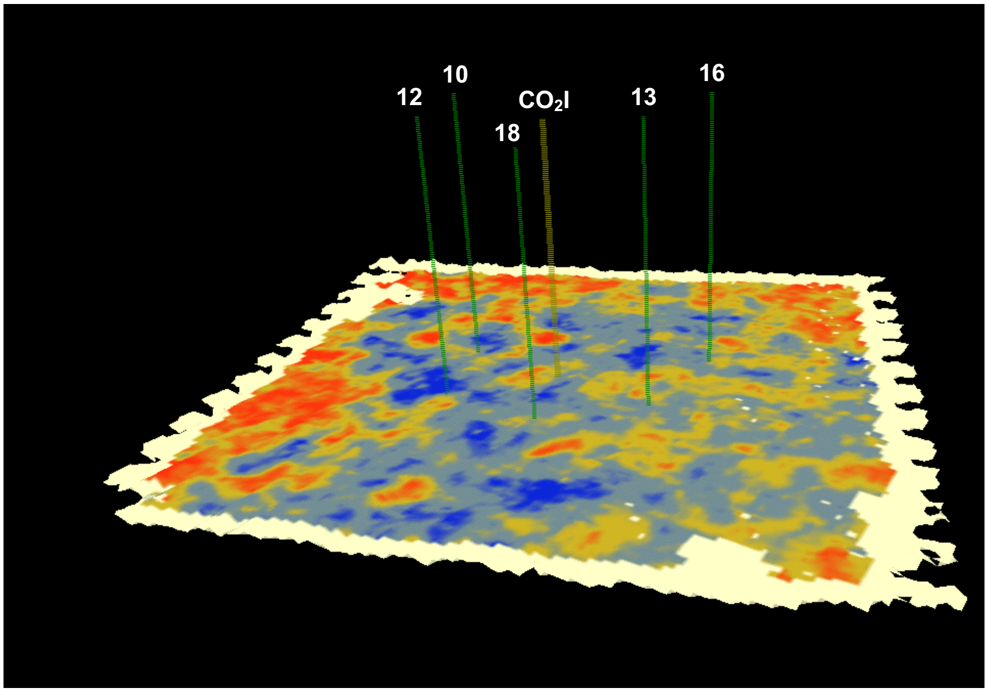

Figure 3: Seismic similarity "lithofacies" map; sinuous-to-linear, isolated pod-shaped, and apparent parabolic forms with differing reservoir quality are consistent with small scale depositional features that occur within ooid shoal complexes; blue is associated with better reservoir properties.

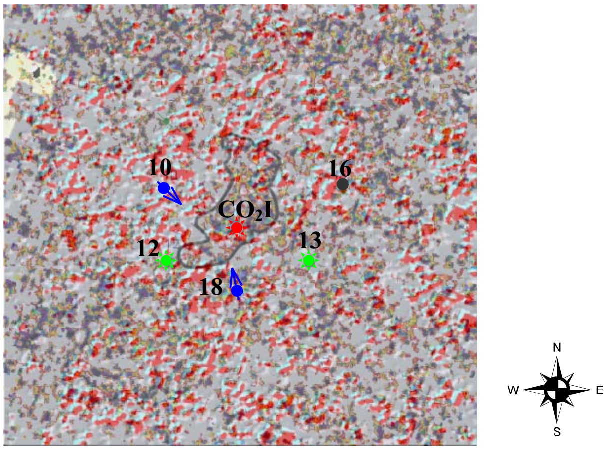

Figure 4: Interpreted seismic lineaments (red) map overlaid on PPB results of the second (March 2004) TL-survey; NE-SW lineaments trend plays important role in facilitating NE-SW advance of the CO_2 bank.

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